Sapphire and GaN Substrate Materials

2012 DOE SSL Manufacturing R&D Workshop

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Forward Looking Statement

- This presentation contains information about management's future expectations, plans and prospects of our business that constitute forward-looking statements for purposes of the safe harbor provisions under The Private Securities Litigation Reform Act of 1995.

- Please see final slide for additional information regarding these statements.

Agenda

- GT Advanced Technologies at a glance
- LED manufacturing roundtable conclusions
- Sapphire substrates
  - Growth overview
  - Substrate fabrication
  - Materials studies
  - Market trends
- Next generation substrates – Soraa ammonothermal GaN
- Summary

GT Advanced Technologies

Diversified crystallization technology leader serving multiple growing industries

ASF™ Sapphire growth equipment

Sapphire substrate materials

Solar

Polysilicon equipment

PV ingot growth equipment

HiCz® materials

LED

Power Electronics

Industrial

Sapphire materials

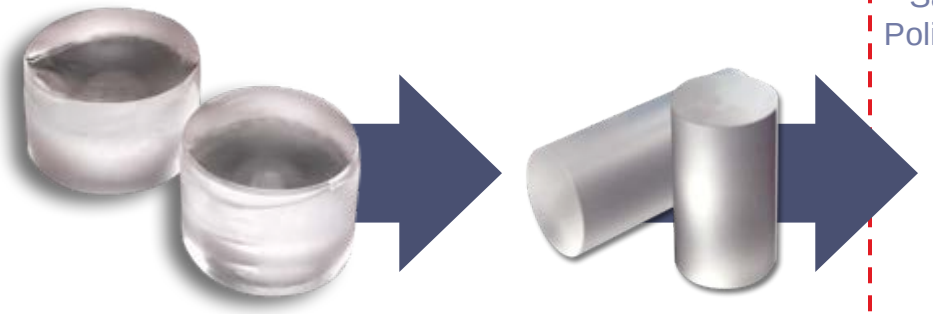
Silicon Carbide (SiC) system

Dual-Focus Sapphire Strategy in LED Market

GT Products

Sapphire Crystal Growth Furnaces

Sapphire Production



Boule Growth

Core Fabrication

Equipment Supplier: GT sells sapphire crystal growth furnaces (ASF™) to sapphire manufacturers

Materials Substrate Developer: Working with leading companies in LED value chain to develop sapphire solutions to market demands then share these market opportunities with our equipment customers. Salem is operationally an R&D facility first.

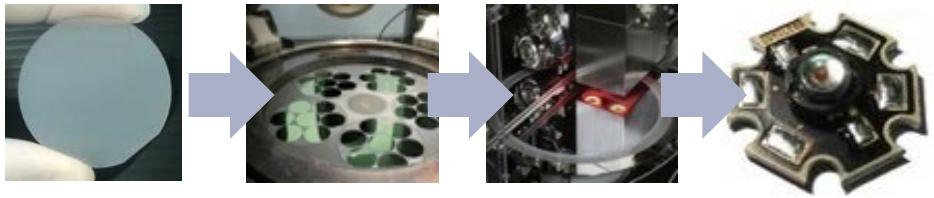
Downstream LED Operations

Sawing/Lapping/ Polishing/Packaging

MOCVD

LED Fab/Die Dicing

Finished LED



Epi-Ready Wafer Fabrication

Epi Wafer Fabrication

LED Chip Fabrication

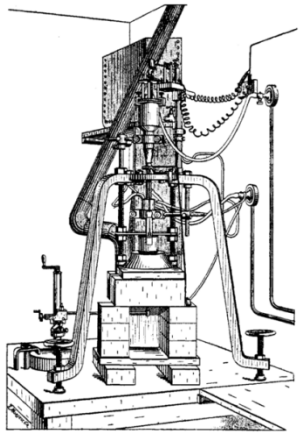
Assembly

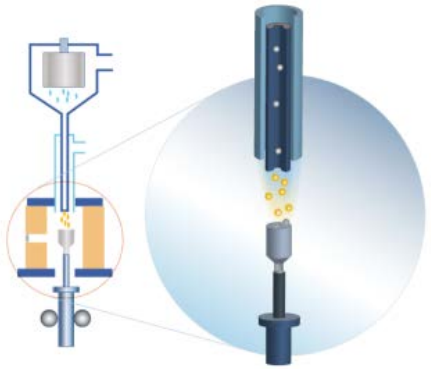
LED Manufacturing Roundtable Substrates Summary

- There is a need for *larger substrates* which would drive the need for larger scale equipment and reduced raw materials costs
- *Improved quality and consistency* of products is required along with standard *specifications*
- Bulk growth processes need to be *better understood and controlled*
- There is a need for improved substrate fabrication processes
- There are opportunities for wafer *standards* to drive efficiency and consistency within the industry; such standards would greatly *clarify raw material requirements* and help determine which substrate manufacturing processes are best, leading to *cost reductions*
- Substrate manufacturing could become a new priority task, however, improvement to substrate manufacturing *will have a small impact on overall cost reductions* for LED manufacturing
  - Caveat 1: Sapphire material and substrate can have a downstream effect on yield
  - Caveat 2: Soraa's GaN substrates are viewed as enabling a whole new class of devices with the intent of decreased $/klm

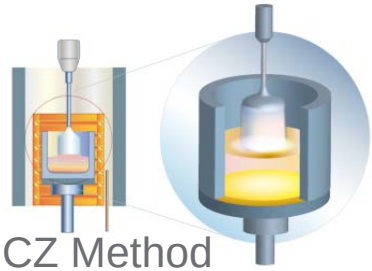
Sapphire Growth Methods

- First methods to grow sapphire developed around 1890, Verneuil Method.
  - Feed powder fed from top, crystal manually pulled to keep at correct distance from flame.
- Today over 60% of the world's sapphire is still using this fundamental concept
  - Pulling/rotating the seed to create a crystal
  - Top-down growth

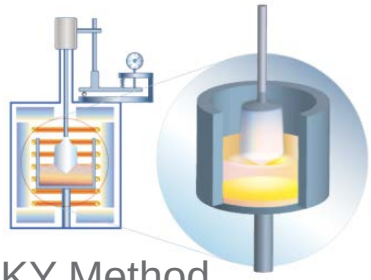




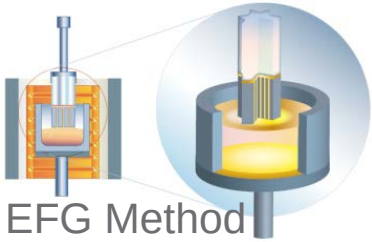
Verneuil Method



CZ Method



KY Method

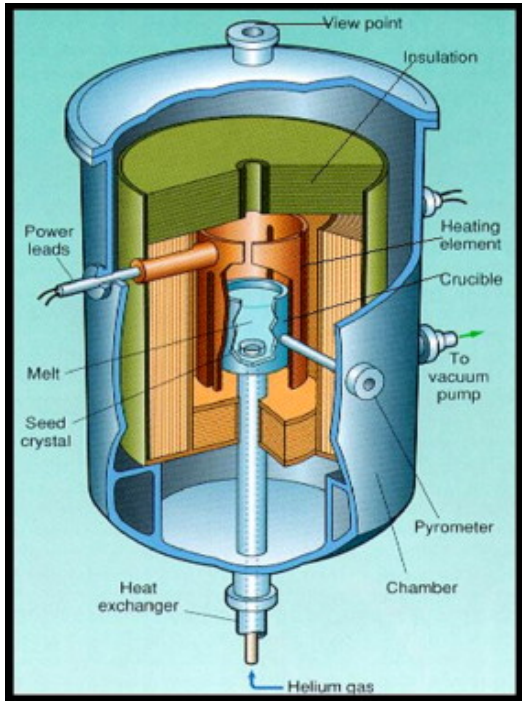


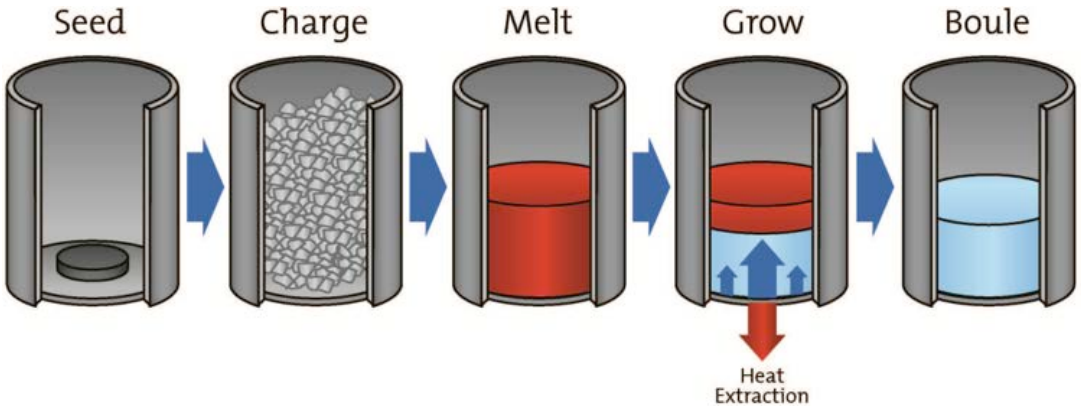
EFG Method

ASF Sapphire Growth Method

- The Heat Exchanger Method (HEM) was created to provide improved repeatability, improved quality, and scalability.

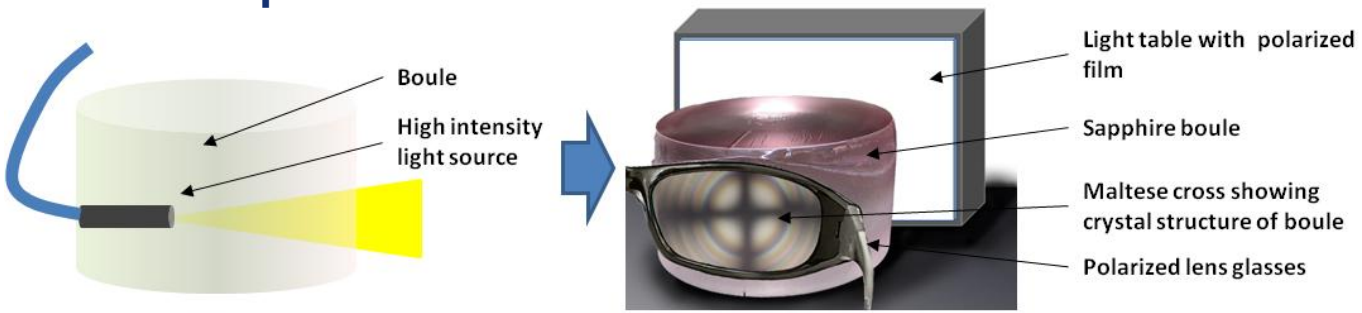
- HEM consists of stationary process with the heat exchanger being used to drive the crystallization



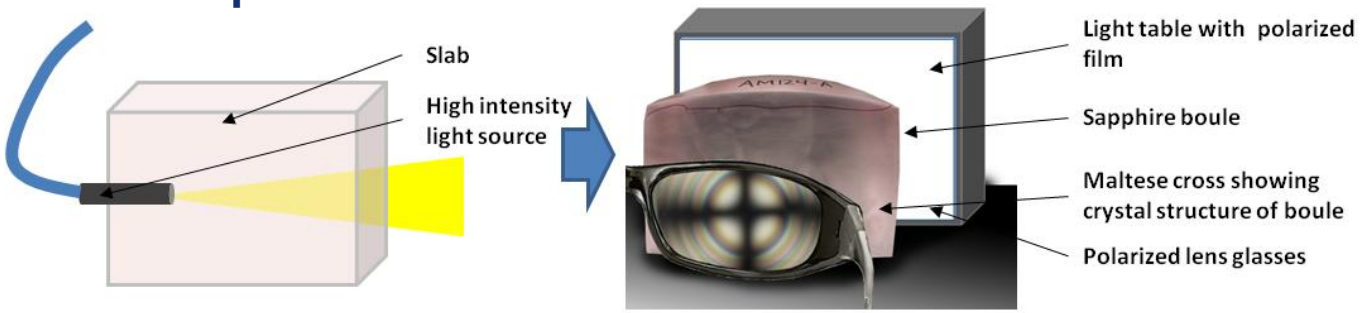


Material Inspection and Allocation

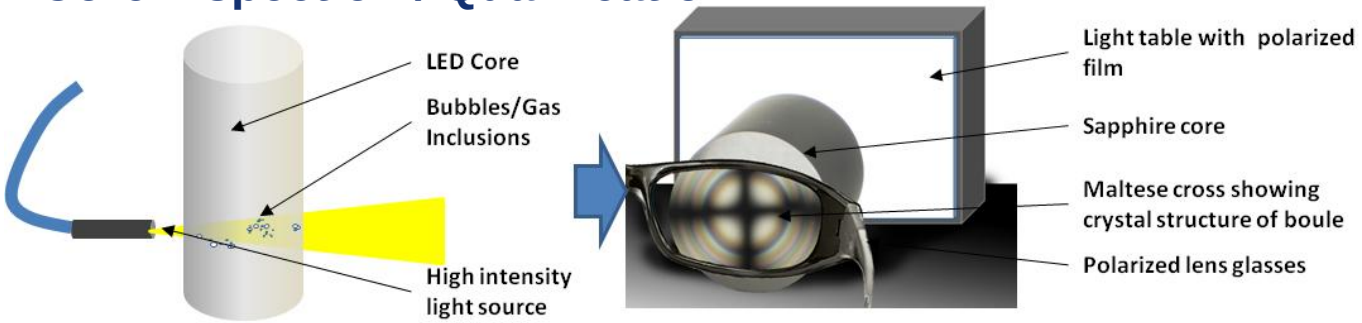
Boule Inspection

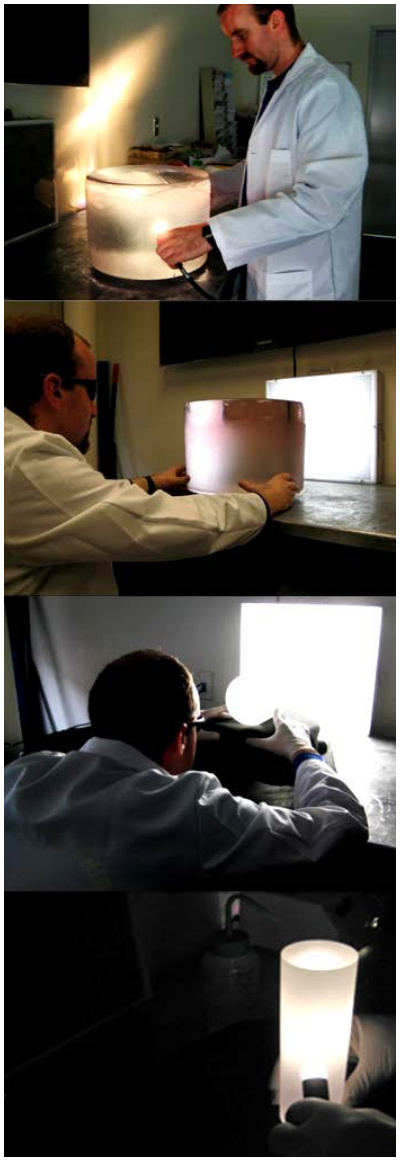


Slab Inspection / Allocation



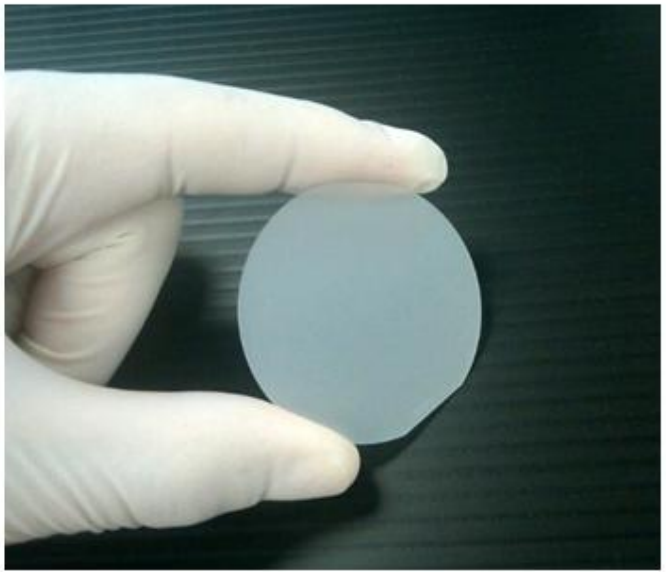
Core Inspection / Qualification





General Core-to-Wafer Process Flow

EPI READY WAFER FABRICATION



Sapphire “Metrics that Matter” Study

INPUTS: Measurable Fundamental Properties of Sapphire

▪ OHT (metrology of low angle grain boundaries, crystal structure, bubbles)	▪ Interferometry Transmission (200-800 nm) ▪ GDMS (elemental analysis)	▪ Color Analysis of Materials (color measurement) ▪ X-Ray (crystallographic analysis)	▪ Laser Inspection and LED Surface Metrology (pre- and post-epi automated laser wafer inspection)	▪ X-Ray Diffraction (crystal micro-structure) ▪ Physical Properties

PROCESS: LED Process Variables and Macroscopic Interactions

(GT Advanced Technologies)	Wafering Study (3rd party)	MOCVD Study (3rd party)	LED Device Fab (3rd party)	LED Luminarie (3rd party)
▪ Crystal Growth (yields, process) ▪ Finishing of Cores (process)	▪ Wafering of Cores (process and performance) ▪ Epi-Wafer Analysis (wafer yields, Ra, TTV, Bow Warp) ▪ Wafer EPD Analysis (pits/cm²)	▪ Epitaxial Growth (process and performance) ▪ Photo Luminescence (LED light metrology, wave-length, color brightness) ▪ Leading LED Metrology Co. (post-epi automated laser wafer inspection)	▪ LED Fabrication (process and performance) ▪ Electrical Performance (forward voltage, reverse leakage, etc.) ▪ LED Light Performance (peak wavelength, bright-ness, binning)	▪ LED Lamp (proof of concept)

OUTPUTS: Yields, Device Perfromance, Economics

▪ LED Material Yields (mm, quality, cost)	▪ LED Wafer Yields and Quality (wafer yields, wafer geo-metrics, cost per wafer)	▪ Epitaxial Yields and Performance (epitaxial efficiency, low defects, performance)	▪ LED Device Yields (device color binning, brightness, electrical performance)	▪ Luminarie (esthetics, performance, brightness, life)

Total of 25 cores, over 2,000 wafers, from 4 sapphire growth technologies were processed across the entire LED manufacturing process

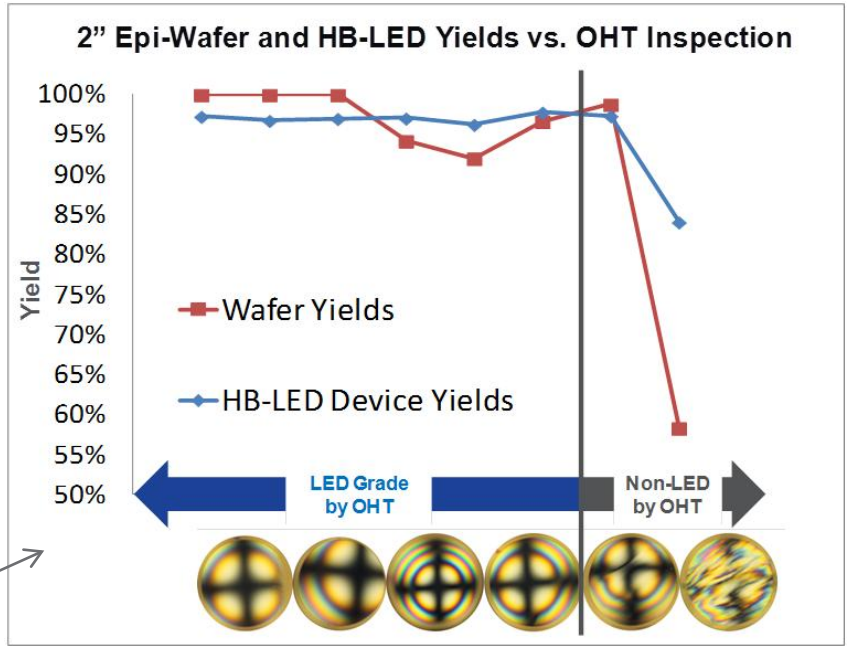
Full results at www.gtat.com

Blind, third-party study at a statistically-significant level with LED industry experts to evaluate Sapphire material performance throughout the **entire LED value chain**

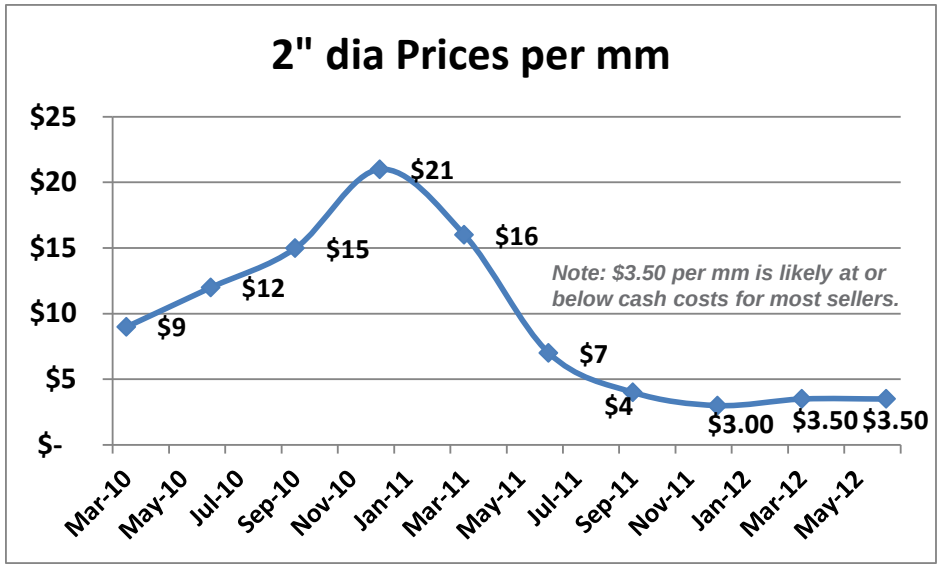
- *Complete traceability back from LEDs to specific wafers to specific cores*

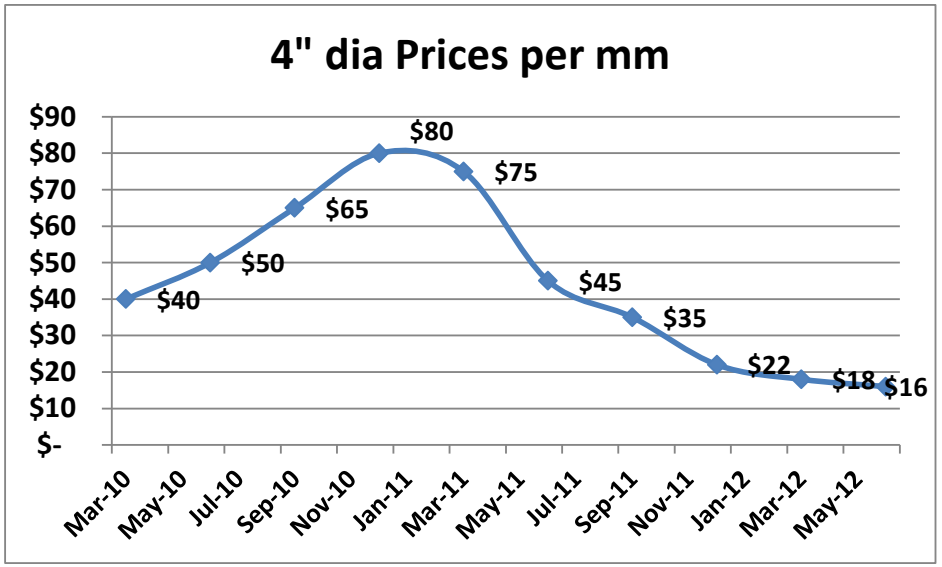
“Metrics that Matter” Findings

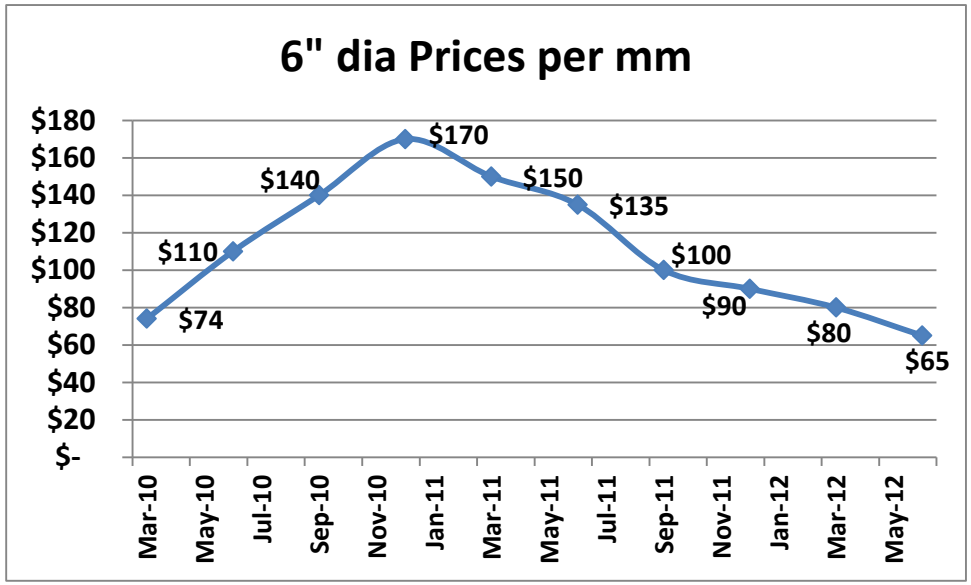
- Material quality and growth impacts wafer yield and quality metrics
- Sapphire growth method impacts performance in epi and LED die fabrication
- Epi-wafer and HB-LED device yields were at, or above, baseline yields and only showed yield losses for material graded significantly below what GT grades in Salem as well as trains ASF customers as LED Grade
- Yield, yield, and yield…



LED sapphire material prices' rate of decline has slowed – 2" and 4" dia sellers appear to be pricing at cash costs or lower







- 2" and 4" prices both down ~80% from peak
- 6" price down ~60% from peak

Source: GT management estimates.

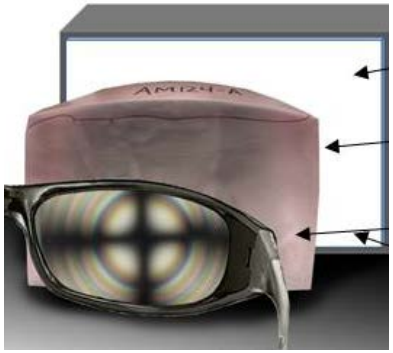
Diameter Adoption Rates and PSS – Interconnected?

- Established tech leaders at 6” and not much PSS
- New entrants need to walk before they run – will stall the adoption of 6” diameter materials, while they master 2” and 4” yields
- PSS is a big deal
  - Not new, but surprising pace of adoption in past 6 months
  - Considered by many to be a must-have for new entrants to compete on brightness and yields of acceptable LEDs
  - The rise of PSS foundries and other specialists
  - Merger of CrystalWise and SAS based on PSS
  - New dynamics of PSS capabilities and IP (design, wafer patterning, MOCVD processes)
- PSS adoption likely to slow the overall adoption of 6”
  - PSS at 2” and 4” seen as priorities

Sapphire Materials Challenges Meeting Wafer Trends

- Process optimization across production process to maximize yield
  - Best done through collaboration between sapphire material producer and customers
  - Systematically define metrics that matter for process control, optimization, etc.

- Move to larger wafer diameters: 2” → 4” → 6” → 8”
  - For sapphire producer requires process and boule geometry optimization to locate larger cores in boule
  - Clarifying what matters will improve sapphire mfgs’ ability to manage costs as wafer sizes increase



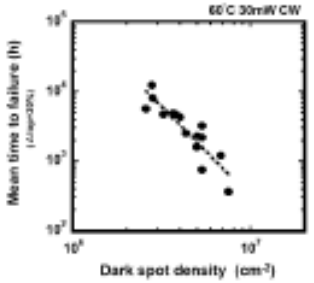
- Standards are seen as a way to ease adoption of optimal material and wafer geometry
  - David Joyce co-chairing 6” wafer geometry task-force for SEMI
  - Luke Glinski co-chairing sapphire defects and measurement task-force for SEMI

Soraa Bulk GaN Development

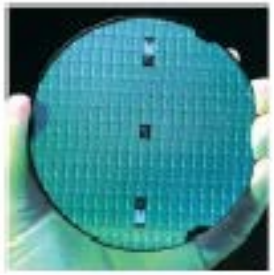
- Virtually all semiconductor technology is based on native substrates
  - Si, GaAs, InP, SiC
  - Better performance, reliability, lifetime, cost

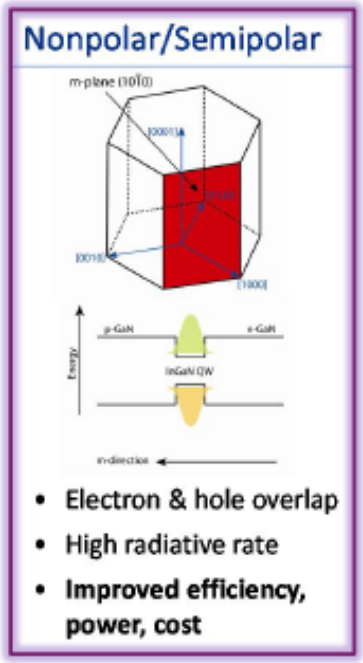
- Advantages for LEDs
  - Improved high-J performance & reliability
  - Simplified architecture, processing
  - Greatly reduced stress, bowing
  - Better MOCVD utilization
  - Nonpolar/Semipolar option

- Bulk GaN substrates available commercially, but:
  - Cost is high – vapor phase process (HVPE) with limited scalability, poor reactant utilization
  - Complex microstructure; defect concentrations too high for electronics



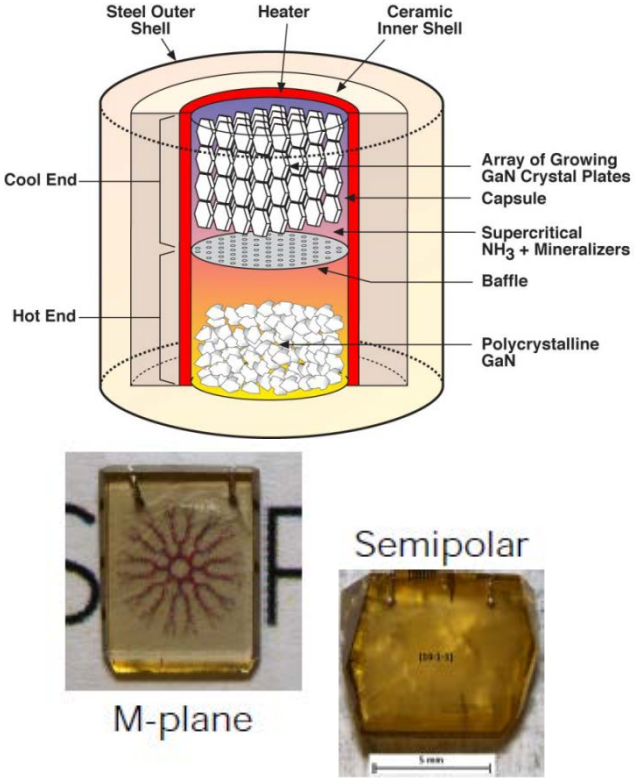
S. Tomiya et al., *IEEE Sel. Top. Quantum Elect.* **10**, 1277 (2004).





Soraa – Unique Approach, Progress

- Ammonothermal GaN
  - Analogue of quartz growth (~ 8000 tons/year, cheap!)
  - 2" diameter, ultralow-defect true bulk GaN crystals demonstrated by AMMONO
  - Significant technical progress by AFRL Hanscom, UCSB, others
  - Challenges:
    - Low growth rates (~ 0.3-4 μm/hr, depending on orientation)
    - High cost, limited scalability of superalloy-based autoclaves
    - Residual impurities
- SCoRA™ – Scalable Compact Rapid Ammonothermal
  - Internally heated – avoids material property limitations
  - Access pressure > 5000 atm; temperature > 650 °C
  - Cheaper, more scalable than superalloy autoclaves
- Results – Crystal Growth
  - Growth of c-plane, m-plane, semipolar crystals 5 mm – 2" diameter, 0.5 – 3 mm thick
  - Growth rates > 10 μm/hr
  - Crystalline quality ~ HVPE routine, dislocation densities < 10^4 cm^{-2} demonstrated
  - Epitaxial quantum well structures grown on SCoRA wafers



Summary

- Sapphire scaling to meet the demands of the industry
  - There are multiple sapphire growth methods – for LED material HEM, KY are dominant
- Understanding the impact of sapphire growth method and material assessment through the value chain can enable sapphire wafer mfgs to focus on the right metrics
  - SEMI standards can help to clarify focus on commercially optimal material
- Ammonothermal GaN is being developed by Soraa as a competing offering to enable lower defects and new GaN orientations
  - Emphasis is on more light output per unit area
- For more info:
  - www.gtat.com
  - www.soraa.com

Forward Looking Statements

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